

Robust and radiation-tolerant optical frequency comb for spaceborne photonic frequency reference generator

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ABSTRACT

We have developed the spaceborne photonic precision microwave frequency reference for the next-generation Japanese satellite navigation system which consists of an iodine-stabilized laser and an Er-doped fiber mode-lock laser based optical frequency comb. As the estimated total dose of the radiation during the operation is more than 160 krad, the highly-radiation-tolerant optical frequency comb has been developed which is based on a radiation-hardened high-concentrated Er-doped fiber mode lock laser with low phase noise. The phonic breaching effect of the Er-doped fibers caused from the 976-nm pumping laser is also investigated.

Keywords: satellite navigation system, mode-lock laser, highly radiation tolerance, photo breaching, photonic local

1. INTRODUCTION

Japanese satellite navigation system: Quasi Zenith Satellite System (QZSS) named 'Michibiki' has been promoted by Japanese Cabinet Office and JAXA since 2018, which consists of seven constellating satellites along the quasi-zenith orbit, and the next-generation QZSS projects with higher positioning accuracy has been also progressed. One of the key technologies for improving positioning accuracy is higher stable on-board microwave reference[1]. The current on-board microwave references are rubidium (Rb) -atomic clocks whose frequency stability is limit to 10^{-13} level, and in order to improve the frequency stability of the on-board clock, we proposed photonic precision microwave generator called IPLOS (iodine photonic local oscillator system) which consists of a highly-stable optical frequency reference and a frequency down converter. As the optical frequency reference, we have developed the iodine-stabilized 1.54- μm laser. The third-harmonics (THG) of the laser frequency is stabilized in reference to the saturated absorption of iodine molecules at 515 nm whose frequency stability reaches 10^{-15} level[2]. The stable carrier frequency of the iodine-stabilized laser around 200 THz can be down converted to 51 MHz by using an optical frequency comb without degradation. For the optical frequency comb, the erbium (Er)-doped-fiber based all-PM(polarization-maintained) NALM (nonlinear amplifying loop mirror) figuer-8 mode-lock lasers have been developed whose longitudinal mode is phase-lock to that of the iodine-stabilized laser, and the stable microwave is obtained from the f_{rep} beat of the phase-locked mode-lock laser. Our mode-lock laser has highly robustness due to its all-PM fiber configurations, and has low phase noise which is comparable to those of conventional figure-9 NALM or NPR (nonlinear polarization rotation)-type fiber mode-lock lasers. Although its high robustness against external perturbations, it is very easy to boot mode-locking operation by a certain pump LD power control procedure, which is called "self-starting", and its self-starting success rate of our mode-lock laser is more than 99.0 % in 10000 trials. As a spaceborne laser, prescribed environment tests were applied to our mode-lock lasers, and our lasers passed the thermal vacuum and vibration test. However, in the radiation test, the mode-locking operation of our laser was terminated by the gamma ray exposure. Therefor we tried to develop highly radiation-tolerant Er-doped mode-lock lasers which keeps mode-locking operation safely against required radiation dose of more than 160 krad.

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2. RADIATION TEST OF MODE-LOCK LASER

Figure 1 shows the schematic of our figure-8 type NALM mode-lock laser. At the NALM part (left ring), a non-reciprocal phase shifter (NRPS) and two Er-doped fibers (EDFs) with different concentration (80 dB/m and 7dB/m) are installed which is pumped by 976-nm laser diodes through wavelength-division multiplexer (WDM). Right ring part is coupled with the left ring by a 2x2 3-dB PM fiber coupler, and the light propagation in the right ring is limited to counter-clockwise direction by an optical isolator. The dispersion of the cavity is designed as the stretched-pulse condition, and our figure-8 NALM laser realizes mode-locking operation with the f_{rep} of 51 MHz and the 3-dB optical bandwidth of more than 50 nm.

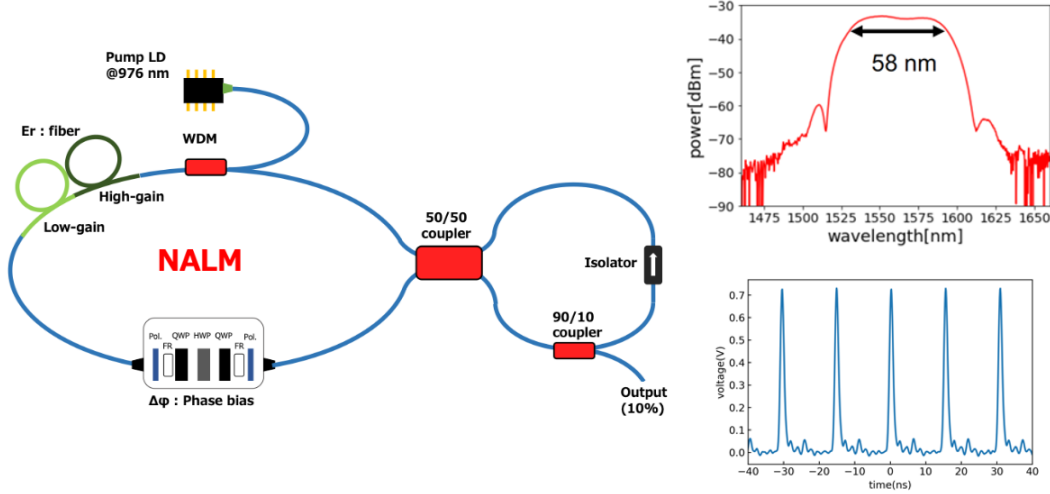


Figure 1 Schematic diagram of of our mode-lock laser. Spectral bandwidth is 58 nm (right upper: optical spectrum) and repetition rate is 51 MHz (right lower: pulse train).

The radiation tests were applied to our mode-lock lasers at the radiation test facility in Institute of Science Tokyo where our lasers are irradiated by gamma ray from ^{60}Co . In the initial test, our mode-lock laser was irradiated by gamma ray with the intensity of 5.12 krad/h under mode-locking operation. Figure 2 shows the spectral evolution of the irradiated mode-lock laser at the the initial radiation test. Horizontal axis is applied radiation total dose [krad], the vertical axis is the wavelength of the spectra, and the color indicates the power of the optical spectra. As can be seen from fig.2, the mode-lock operation of our laser was terminated at the total dose of 35 krad, and was never recovered. It is reported that the gamma ray radiation causes radiation-induced absorption (RIA) to EDFs [3], which would lead to the change of dispersion or increase of loss in EDF. The soliton mode-lock laser has some peaks in its optical spectrum called 'Kelly sidebands' whose peak wavelength depends on the dispersion of the oscillator. In the additional test, the Er-doped soliton mode-lock fiber laser in the same configuration was irradiated by gamma ray, and, in that test, the peak wavelength of the Kelly sidebands shows little changes before the termination of the mode-lock operation. Therefor it is said that the termination of the mode-locking is caused from not the dispersion change but the increase of the cavity loss.

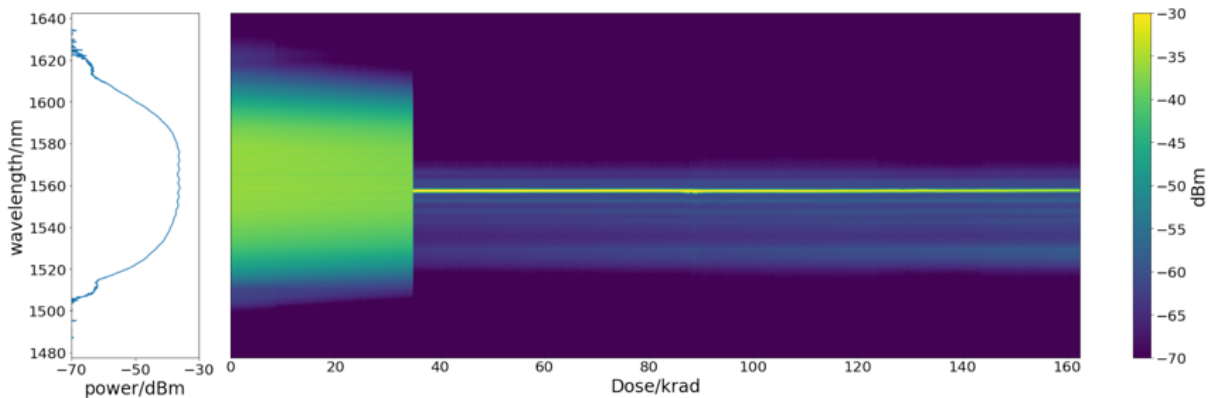


Figure 2 Variations of the optical spectrum of our mode-lock laser to the irradiated total dose.

In our system, Er-doped fibers are used in three parts: oscillator of the mode-lock laser, an Er-doped fiber amplifier (EDFA) to obtain f_{ceo} beat note of the mode-lock laser, and EDFAs for the iodine-stabilized laser to obtain THG, and hence the RIA in the EDFs are serious problems for our system. Therefore we applied radiation test to the oscillator of the mode-lock laser and EDFAs for investigating RIA effects on our system.

In order to enhance the radiation tolerance of our mode-lock laser, we try to replace the normal Er-doped fibers in our cavity with radiation-hardened (RH) Er-doped fibers. The radiation hardened fiber usually contains additional doping materials such as cerium (Ce) for enhancement of radiation tolerance [4], and therefore it is hard to make highly-Er-doped radiation-hardened fiber due to the concentration quenching (decreasing of upper-state lifetime), which is not commercially available. We ask Exail (iXblue) company to make specially-customed highly-Er-doped radiation-hardened (RH) fibers with the concentration of 80 dB/m and 40 dB/m, whose RIA is 0.044 dB/m/krad and 0.0056 dB/m/krad, respectively. We made a figure-8 NALM mode-lock laser with RH 80-dBm EDF, and second radiation test was applied to this mode-lock laser. In this test, the mode-locking operation is terminated at the total dose of 25 krad which shows shorter lifetime than that of the previous mode-lock laser with normal 80-dB/m EDF (fig.3-a). It is because that little improvement of the RIA is observed in the RH-80dB/m EDF, and the effective gain loss of the EDF due to concentration quenching would overcome the improvement of the RIA.

The second candidate is the custom-ordered RH-40dB/m EDF which has ten-times lower RIA than that of higher concentrated RH-80dB/m EDF, and the expected loss is comparable to that of the normal 80 dB/m EDF.

As the next step, RH-80dB/m EDF in the mode-lock laser cavity is replaced with the RH44-dB/m EDF. By optimizing the cavity design of the mode-lock laser, the optical property of the mode-lock laser with RH44dB/m EDF is almost the same as that of previous one (fig.1), and higher self-start success rate of more than 99.7% is obtained. Then the radiation test was also applied to this mode-lock laser with RH-44dB/m-EDF. In this test, the mode-locking is kept stable for the total dose of more than 160 krad (fig.3-b), and it is concluded that our mode-lock laser with RD-44dB/m EDF satisfies the radiation requirement of 160 krad.

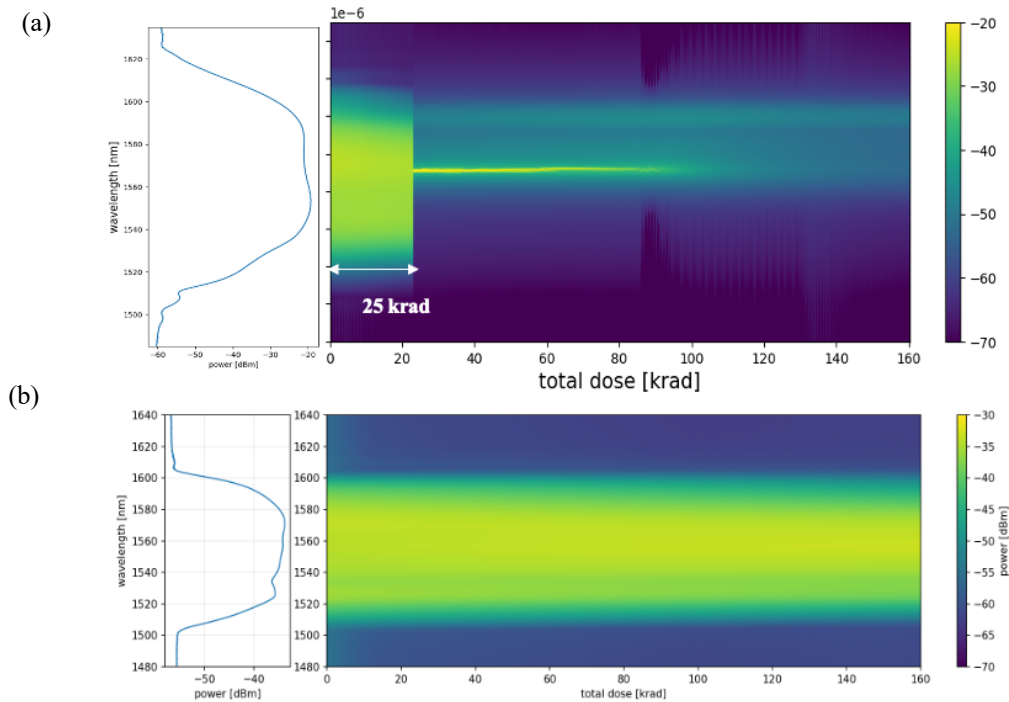


Fig.3 Evolution of the optical spectra to the radiated total dose. (a) MLL with RH-80dB/m EDF (b) lower MLL with RH-40dB/m EDF

3. RADIATION TEST OF EDFAs

The radiation tests are also applied to EDFAs for investigating detailed mechanism of radiation effect to EDF. A few mW of a continuous-wave (cw) master laser light from an external-cavity laser diode (RIO:ORION 0185) is amplified by the normal-80dB/m EDFAs which are pumped by 976-nm LDs or 1480-nm LDs, and temporal variations of the output power are monitored while EDFs are irradiated by gamma ray (figure.4-a). It is seen that the output powers from the EDFAs are exponentially decreased due to RIA, and the power decreasing rate of the 976-nm-pumped EDFA (blue trace) is smaller than that of the 1480-nm-pumped EDFAs (orange trace). The energy diagram of the Er-ion is shown in Figure4-(b). When EDF is pumped by the 976-nm LD, the ions at the ground state ($^4I_{15/2}$) are excited to the metastable state ($^4I_{11/2}$), and after non-radiative decaying to the lasing upper state ($^4I_{13/2}$), they decay to the ground state ($^4I_{15/2}$) to generate 1550-nm coherent light. A part of pumped ions at metastable state ($^4I_{11/2}$) successively absorb another 976-nm photon to excite higher $^4F_{7/2}$ state (excited state absorption: ESA), and then radiative decay to the ground state ($^4I_{15/2}$) to generate higher energy photon around 500 nm. These higher energy photons recover a gamma-ray damaged EDF called "photo breaching"[5], which is not observed in 1480-nm-pumped EDFA. As in the amplifying operation, the RIA effect is effectively suppressed by photo breaching, the 976-nm pumped EDFA shows less power decrease, which is called real-time photo breaching

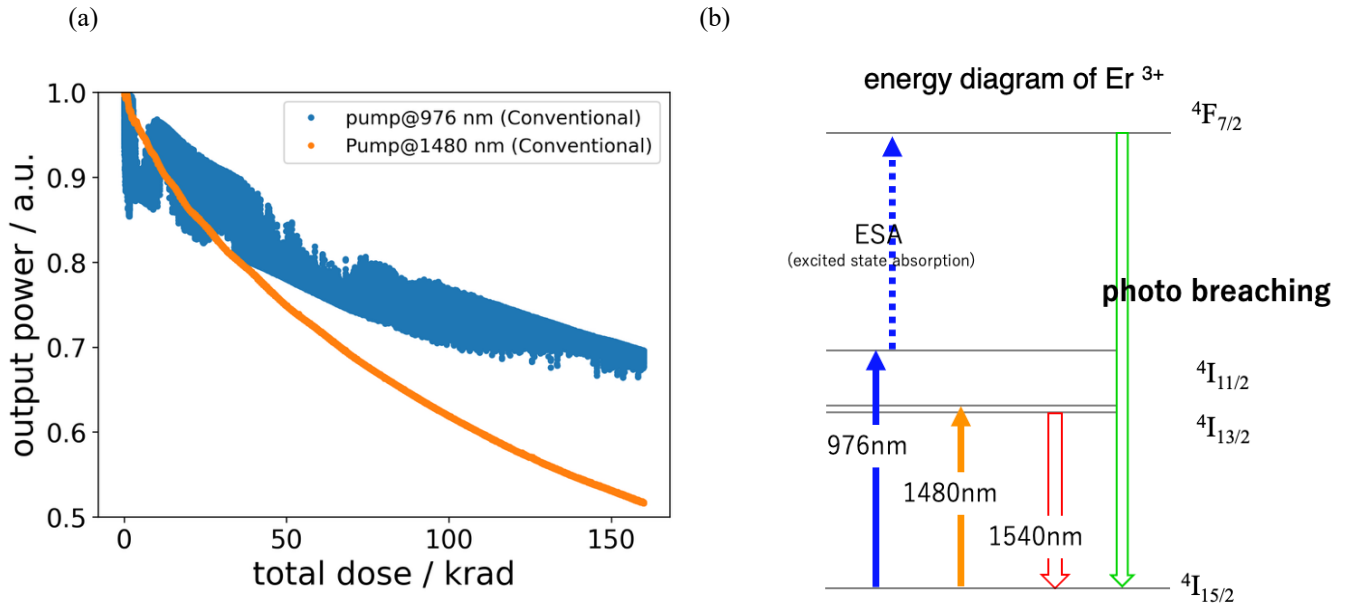


Figure4 (a) Output power variation of the 976-nm pumped EDFA(blue) and the 1480-nm-pumped EDFA(orange). The degradation rate of blue-trace is smaller than that of orange trace due to photo breaching (real-time photo breaching). (b) Energy diagram of Er ion

After 160 krad radiation, radiation-damaged EDFAs are operated by pumping 976-nm LD without illuminating gamay . In that case, the output power of EDFs are recovered due to the 976-nm-pump, which is called "post photo breaching" (fig.5).

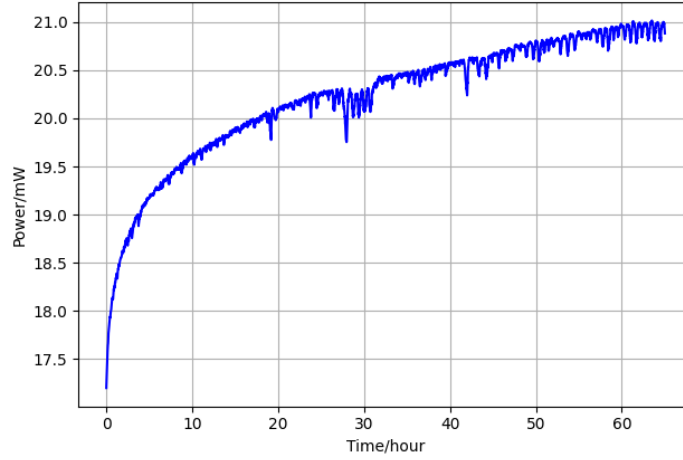
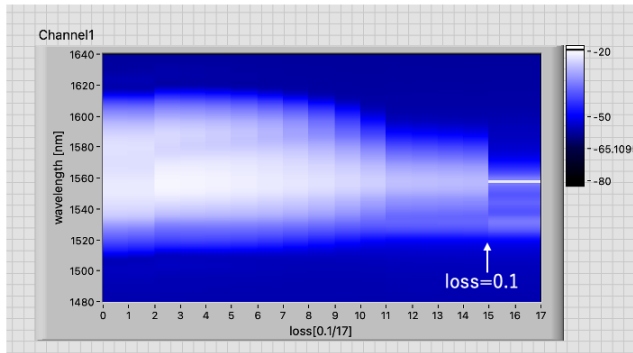


Figure5 Radiation-damaged fiber is recovered by 976-nm amplifying operation

4 RESULTS AND DISCUSSIONS

As the mode-locking operation of the fiber mode-lock laser is very sensitive to the cavity loss of the oscillator, the mode-locking operation of the irradiated mode-lock laser is terminated mainly due from the RIA driven cavity loss, and RH-EDF with smaller RIA increases the radiation tolerance of the laser and extend the lifetime. In order to investigate the condition and the threshold of the mode-lock operation, the additional cavity loss is applied by using a voltage-controlled PM fiber attenuator (Thorlab V1550PA) in the NALM ring of the figure-8 fiber mode-lock laser with Normal 80 dB/m EDF (the same configuration as fig.1). The result is shown in Fig.6(a). Horizontal and vertical axes are optical spectrum and additional loss in the cavity [A.U.]. As the additional loss increases, the optical bandwidth of the MLL is gradually decreases, and when the additional loss reaches 0.1 (10%-loss), the mode-locking operation is terminated. From the result, it is assumed that then 10% of additional cavity loss is the threshold for keeping stable mode locking operation. Figure 6(b) shows the output power variation of the irradiated EDFAs (red trace: RH-40dB/m, green trace: Normal-80 dB/m, blue trace: RH-80dB/m). As can be seen from the figure5(b), the degradation of RH-80dB/m and Normal-80dB/m EDFAs reach 0.1 (indicated by dotted line) at around 30 krad total dose, while output of RH-40 dB/m EDF keeps more than 90% of its initial value before 160 krad radiation.

(a)



(b)

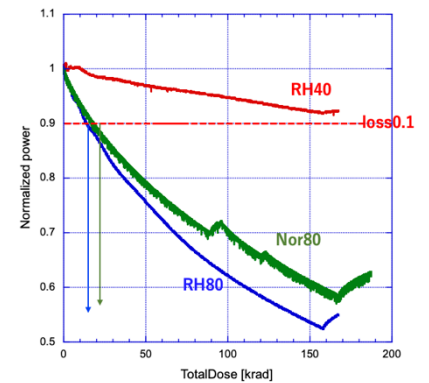


Figure 6 (a) Mode-lock spectra with additional cavity loss. When 0.1% loss is added, the mode-locking operation is terminated. (b) Output power variation of irradiated EDFAs. RH80 dB/m and Normal80 dB/m reaches 0.1% loss at around 30 krad while RH40 dB/m EDF keeps less than 0.1 before 160 krad.

These are consistent with the experimental results that the mode-lock laser with RH- and Nor -80dB/m EDFs are terminated at total dose of around 30 krad, and MLL with RH-40 EDFA keeps stable mode-locking after illuminated 160 krad of radiation.

Our radiation test is the acceleration test in which total dose obtained in 15-years operation is illuminated for only a few days. In that test, the radiation intensity is much higher and RIA effect is much stronger than that at the orbit while the photo-breaching effect is the same as that in real on-orbit operation. As the power degradation rate of EDFA determines the balance of RIA and photo-breaching, the operation lifetime of our MLL on orbit would be much longer. For precision quantitative estimation of laser lifetime on orbit, additional radiation test of EDFAs with different radiation intensities are now under planning.

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